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Unsteady hydrodynamics of full-scale tidal turbines

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Summary: Due to the lack of full-scale measurements of the flow around tidal turbine blades, it is not clear if unsteadiness in the background flow can induce dynamic stall and the significance of this on the rotor's performance. To investigate, we develop a model that couples dynamic stall, rotational augmentation and blade element momentum theory with real flow measurements. We found that large, realistic waves lead to large fluctuations in power and thrust, mostly due to inviscid unsteady hydrodynamic effects near the blade tip. Conversely, flow fluctuations have little effect on the rotor's mean thrust and power.

Introduction

The marine environment is inherently unsteady due to waves and turbulence. When a rotor blade translates through unsteady flow, the rotation causes a time dependent flow field that can lead to load hysteresis, stall delay and dynamic stall (DS). To date, the quantification of unsteady loading on tidal turbine blades is an open question. Milne *et al.* [1] carried out experiments on a scaled turbine by oscillating it in a towing tank. At lower tip-speed ratios, they found the flow was largely separated over the blade span, which for high-frequency forcing caused the root bending moment to exceed the quasi-steady value by up to 25% due to DS. Galloway *et al.* [2] tested the effects of waves using a wave tank to generate linear waves. The experimental results showed that the median value of the root bending moment was exceeded by up to 175% during the presence of large waves. Contrarily to Milne *et al.*, the authors concluded that the effect of DS was limited and, therefore can be neglected in some cases. Other than the work of Milne *et al.*, no documentation of DS occurring on tidal turbine blades exists. Yet, it is known to occur on all types of horizontal-axis wind turbines, due to a combination of shear, turbulence, yaw misalignment and tower shadow effects [3]. Since tidal turbine blades will also experience these effects with the addition of waves, it is likely that dynamic stall occurs. In addition, the difference between the mean value and the steady state has yet to be quantified. The first aim of this work is to investigate if DS occurs in large, realistic waves. Secondly, it aims to quantify the differences between the resulting unsteady loads with those predicted with a commonly-adopted quasi-steady approach, which does not account for load hysteresis, stall delay and DS.

Method

A model has been developed, which couples a blade element momentum (BEM) [4], rotational augmentation [5] and DS models [6] to determine the unsteady blade loads. Induction factors are computed using a running average of the unsteady forces over a period of revolution. The rotor power and thrust are computed for a 3-bladed, 18 m diameter rotor. The blade profile follows that described by Gretton [7]. All blade sections comprise uniform thickness NREL S814 profiles. Velocity field measurements recorded during the ReDAPT project are used as an input to the model [8]. We consider a 256 s flow sample measured during a flood tide at the European Marine Energy Centre which includes an energetic wave train of ca. 5 m height and 10 s apparent wave period. The wave steepness, defined as the product of wave amplitude and wave number is approximately 0.17, indicating that the wave is weakly non-linear. The channel depth is 45 m and the hub depth is 27 m. The depth profile of the streamwise velocity (u) follows a power law with exponent 0.162, and it is 2.70 ms^{-1} at the hub. The magnitude of u averaged over the swept area and the sample period is $\bar{u} = 2.72$ ms^{-1}, while $\sqrt{\overline{u^2}}$ is 2.74 ms^{-1} and $\sqrt[3]{\overline{u^3}}$ is 2.77 ms^{-1}. The latter velocity is used for the steady simulation and to nondimensionalise forces, torque and power.

Results

The tip-speed ratio ($\lambda = 4.5$) and blade pitch ($\beta = 0.1°$) that maximise the power coefficient $(C_P = 0.47)$ in a uniform constant current of velocity $\bar{u}$ are determined using the BEM model, where the static coefficients are corrected for rotation. All simulations are carried out using these parameters. Figure 1a-b show the power (C_P) and thrust (C_T) coefficients, respectively, over 10 rotational periods (T_r = 4.5 s). Results are presented for a uniform constant (steady) velocity and for the measured unsteady conditions. Unsteady fluctuations are clearly dominated by the period of the wave, with no discernible contribution from T_r. Fluctuations in C_P and C_T were found to exceed the steady value by almost 50% and 25%, respectively. Conversely, small changes are observed in the mean power and thrust coefficients, which both decrease by about 3%.

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Time averaged, sectional lift ($\overline{C_L}$), drag ($\overline{C_D}$), thrust ($\overline{C_T}$) and torque ($\overline{C_Q}$) coefficients are shown in Fig. 2a-d, respectively. These coefficients are computed for steady, quasi-steady and unsteady conditions. The quasi-steady values are determined using static wind tunnel data [9] and, hence, do not take into account DS nor linear, inviscid, unsteady effects (*cf.* Theodorsen theory). The radial coordinate of the section (r) is normalised by the turbine radius (R). Each coefficient is maximum near the root, where the angle of attack is higher, and decreases towards the tip. Near the root, however, the unsteady values are significantly higher than the quasi-steady values, which more closely follow the steady values. This is due to the occurrence of DS. Conversely, near the tip, the unsteady values are lower than the quasi-steady values, which indicates that the unsteady effects are of a linear type. Compounded with the higher tangential velocity and longer moment arm, the lower sectional torque ($\overline{C_Q}$) and thrust ($\overline{C_T}$) near the tip lead to the reduction in the rotor's mean power and thrust, as observed in Fig. 1.

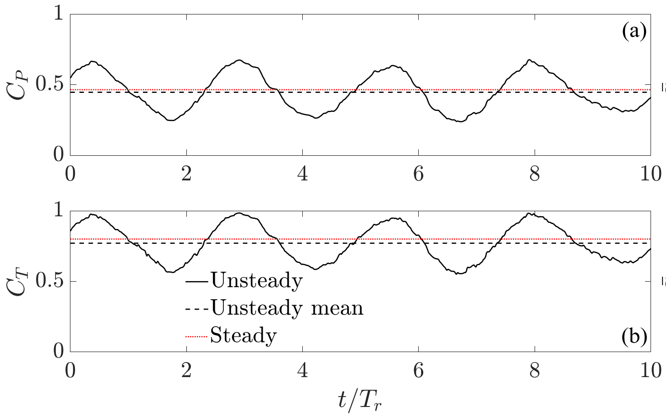

Fig. 1. Time series of (a) power coefficient and (b) thrust coefficient.

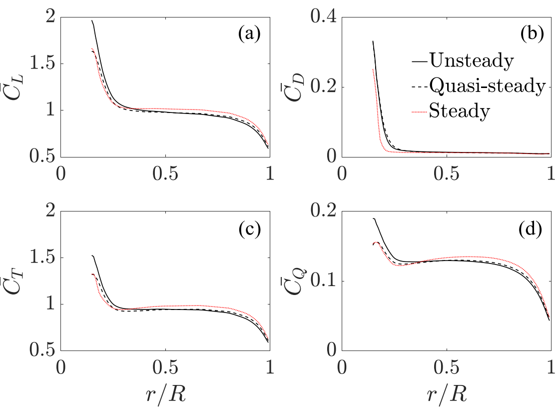

Fig. 2. Mean sectional coefficients of (a) lift, (b) drag, (c) thrust and (d) torque.

Conclusions

Large, realistic, waves conditions result in extreme fluctuations of the forces on the blade. The governing frequency is that of the wave, not the rotational frequency. The amplitude of the power and thrust variations are ca. 50% and 25% of their mean values. Dynamic stall occurs in the inner sections of the blade, but due to the low tangential velocity and small moment arm, it has a negligible effect on the rotor's performance. Conversely, linear, inviscid, unsteady effects at the tip result in a reduction of the maximum load fluctuations and of the rotor's mean power and thrust. These results show that large waves induce significantly large load fluctuations, however, there is little effect on the mean performance of the rotor.

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